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SYNTHETIC APERTURE SONAR

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THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

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13. ABSTRACT

This report discusses synthetic-aperture imagery applied to the Seabed Treaty verification problem. It presents the basic theory of the synthetic-aperture side-looking sonar and shows the transition region from real to synthetic aperture in terms of resolution and mapping rate. Considerable engineering and detailed design work will be required to perfect the synthetic-aperture technique. In addition, the form and character of ocean bottom structures housing potential threats and their possible locations must be defined so that the image makers can intelligently develop discriminators and judgment tools. Considerable attention is paid in the report to the signal-processing problem and output display. The paper also discusses development costs, normal development schedules, critical technical areas, critical medium stability experiments, characteristics of possible demonstration hardware, and the state of the art of precise navigation at sea.

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ABSTRACT

Visibility in the ocean at optical frequencies is limited to hundreds of yards under the best of circumstances. The alternate means for "seeing" objects in the ocean is through acoustic imagery. High-resolution acoustic systems are in use to locate small objects such as mines and swimmers; however, these must operate at very high acoustic frequencies to obtain the needed resolution, which because of the extreme attenuation at these frequencies limits their range. Very low acoustic frequencies are used by geologists to penetrate the ocean and map its floor at great depths, however with poor resolution. At intermediate frequencies and with synthetic aperture techniques, imaging of a rather substantial swath of ocean bottom is possible. Synthetic aperture radar imagery today is competitive with optical photography, and there is no reason apparent why with the application of similar techniques acoustic imagery cannot approach radar imagery. However, considerable engineering, detailed design, and demonstration are required in the perfection of the acoustic technique. In addition, the form and character of the acoustic image of potential objects of interest and their possible locations must be defined for discrimination and system deployment reasons.

The report discusses the basic theory of the synthetic aperture side-looking sonar and tradeoffs between real and synthetic aperture in terms of resolution and mapping rate. Considerable attention is paid to the signal-processing problem and output display, as well as the state-of-the-art of navigation at sea. The paper also discusses the development costs, normal development schedules, critical technical areas, critical medium stability experiments, and possible demonstration hardware system characteristics.

This work on high-resolution acoustic imaging has been supported under the Advanced Marine Technology Program of the Strategic Technology Office of the Advanced Research Projects Agency. This report on the application of that technology to the Seabed Treaty verification problem was prepared at the request of the Weapons Evaluation and Control Bureau Field Operations of the United States Arms Control and Disarmament Agency.

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PREFACE

This paper discusses synthetic aperture imagery applied to the Seabed Treaty verification problem. It was written at the request of the United States Arms Control and Disarmament Agency. The concept of "holographic" filling of the synthetic aperture was suggested by Mr. F. E. Nathanson; the discussion on data processing requirements was written by Mr. A. M. Chwastyk, target recognition and identification by Mr. F. C. Paddison, and navigation at sea by Mr. H. D. Black. The major share of unifying the report and the system analysis was done by Mr. J. N. Bucknam.

The Applied Physics Laboratory has been studying the general problem of new techniques for ocean and benthic search and imagery as part of the Advanced Marine Technology Program for the Strategic Technology Office of the Advanced Research Projects Agency.

To a large extent, the synthetic aperture system discussed in this paper was drawn from a very comprehensive study performed by the Submarine Signal Division of the Raytheon Company on the feasibility of synthetic aperture arrays for high resolution ocean bottom mapping (Ref. 1). The system discussed in this paper for the filling of the synthetic aperture array to suppress sidelobes is different from that discussed in the Raytheon reports. The Raytheon system uses a frequency-diversity technique to allow multiple pulses to be in the water simultaneously. The system discussed in this paper uses a coherent, fixed-frequency technique.

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1. INTRODUCTION

Interest in mapping the bottom of the oceans has recently received an increased impetus from the Seabed Treaty development and negotiations. The treaty, which would prohibit the emplacement of nuclear and other weapons of mass destruction on the seabed, has been prepared by the United Nations, and has been ratified by the United States, the Soviet Union, and more than the number required to bring it into force. There is no explicit validation requirement, or technique called out by the treaty for its enforcement.

The United States has demonstrated a limited capability of locating and identifying objects on the ocean floor with the U.S. Navy ship Mizar when she located the submarines Thresher and Scorpion, the submersible Alvin, and the French submarine Eurydice. In addition to systems such as the Mizar's, a system for surveying large ocean or continental shelf regions to select areas for more detailed scrutiny by Mizar type systems is needed.

This paper examines the operational requirements of a Seabed Treaty policing system for continental shelf or deep ocean use and demonstrates the suitability of an acoustic synthetic aperture surveillance system for such a task.

SUMMARY

In the remaining portion of Section 1 operational requirements of a Seabed Treaty policing system are outlined. It is then shown, by way of example, that conventional acoustic imaging systems require excessively long hydrophone array lengths in order to meet these requirements. The synthetic aperture technique is suggested as suitable solution to this problem, and a tutorial description of the operation of a synthetic aperture mapping system is then presented.

Section 2 more fully develops the tradeoffs between conventional and synthetic aperture mapping systems. System coverage rate limits are found parametrically for both systems. Tradeoff curves are then found that divide the coverage-rate/resolution plane into two regions: one in which conventional mapping techniques are desired; the other in which synthetic aperture techniques are preferable. In shallow waters, such as those over a continental shelf, real aperture surveillance systems can be used, producing reasonable resolution, though with limited mapping rates. Real aperture techniques are not useful in the deep ocean. The synthetic aperture is effective in deep water as well as in continental shelf regions.

Cost and schedule estimates are presented in Section 3 for several hypothetical synthetic aperture systems. A research and development program is suggested. Small-quantity production costs are estimated.

Risk areas are identified in Section 4; medium stability, data processing, target recognition and interpretation, and navigational limitations are items discussed. A feasibility demonstration system is suggested.

REQUIREMENTS OF A SEABED TREATY POLICING SYSTEM

From an operational standpoint, the task of Seabed Treaty policing is formidable. Effective policing is tantamount to frequent and thorough mapping of those ocean bottom areas that are potentially suitable for weapon emplacement. At the moment it is uncertain how much area must be mapped and how often the maps must be updated. It is not unreasonable, however, to hypothesize an area 2500 km long and 120 km wide, or an area of 300 000 km^2 (this corresponds approximately to the area of the continental shelf of the U.S.). If it is assumed that a monitoring platform operates for 600 hours per month with the remaining 120 hours used for maintenance and refurbishment, a single platform must map 500 km^2/h to perform monthly surveillance of this area. Several platforms could accomplish the task at a proportionately lower coverage rate per platform.

CANDIDATE MAPPING SYSTEMS

Existing Systems

A survey of the literature (Refs. 1 to 3, and others) and conversations with those in the field indicated that there are three general surveillance systems in use: optical systems with ranges less than 100 meters; mine hunting (scanning) sonars with ranges of perhaps 300 meters; and sidelooking sonars with ranges up to 750 meters. Optical systems, although desirable because of their high resolution, appear to be limited to use at low-coverage rates owing to the severe underwater scattering of light. Acoustic systems are more promising for generalized surveillance, although existing ones are capable of mapping only 1 to 6 km^2/h.

Acoustic Imaging Systems

An acoustic imaging system in its simplest form consists of a linear array of hydrophones of length L_R. The array is mounted on, or towed by, a platform moving at a velocity v. At an acoustic wavelength λ, the azimuthal angular resolution is approximately λ/L_R radians. The basic geometry is illustrated in Fig. 1.

An imaging system of this type, which we shall designate a real aperture system, maps the ocean floor on the basis of return echo strength versus broadside range. Range resolution is achieved by using short pulses (or longer pulses with appropriate receiver pulse compression). Azimuth resolution, ρ, is determined by the width of the receive beam at maximum range:

$$\rho = \frac{\lambda R_{max}}{L_R}.$$

L_R = LENGTH OF REAL ARRAY
λ = ACOUSTIC WAVELENGTH
h = DEPTH OF WATER BENEATH MONITORING PLATFORM
v = PLATFORM VELOCITY
R_s = MAXIMUM SLANT RANGE
R_p = MAXIMUM PROJECTED RANGE
ρ = AZIMUTHAL RESOLUTION

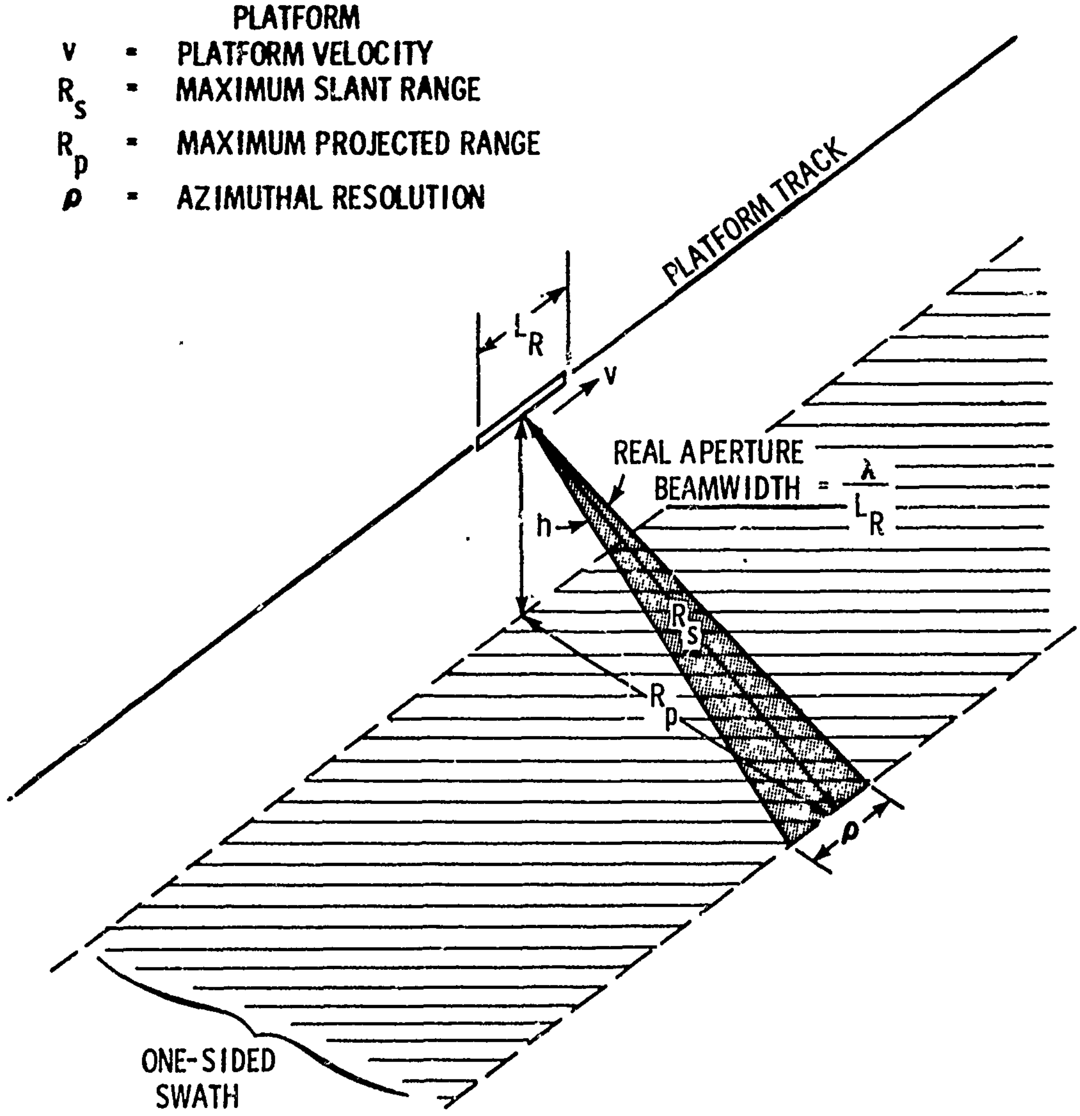

FIGURE 1 REAL APERTURE MAPPING SYSTEM

The limitations of such systems are best illustrated by way of example. Suppose a platform is to map at a rate of 150 km^2/h at a resolution of 3.5 meters. The speed of the platform will be assumed to be no greater than 10 knots in order that propeller cavitation noise attendant at high speeds does not interfere with the acoustic imaging system. At this speed, echoes must be received from a maximum broadside range of about 5 km to achieve a coverage rate of 150 km^2/h. Accustic attenuation effects can be quite severe over such long ranges. These effects, which are frequency dependent, are summarized in Table 1. From this table we can see that a maximum frequency of about 10 kHz is indicated in order to keep the transmitter power within reason.

A 3.5-meter resolution at 5-km range requires a beamwidth of about 0.7 milliradian. The aperture extent must therefore be at least 1400 wavelengths. At 10 kHz the hydrophone receive array must be more than 200 meters long and contain 1400 or more hydrophones, lest grating lobes should appear. Still longer aperture lengths would be required to suppress sidelobe levels without compromising resolution at maximum range. Such arrays appear expensive and impractical.

The need for such excessively long hydrophone arrays can be eliminated by use of the <u>synthetic aperture technique</u>. The technique, which was developed for high-resolution radar imagery, capitalizes on the uniform linear motion of the platform by synthesizing a long array from the stored echoes received by a short array at consecutive positions along the platform track. The system is more complex than a simple real array imaging system in that it requires the addition of appropriate data storage and processing equipment and inertial navigation equipment to provide precise information on platform deviations from the nominal constant speed, straight-line path.

Table 1
Acoustic Absorption (Attenuation)

Frequency, f (kHz)	Attenuation Coefficient, α(dB/km)	5-km Continental Shelf (dB)*	16-km Deep Ocean (dB)*
3.2	0.20	2.0	6.7
5.0	0.37	3.7	12.0
10.0	1.13	11.3	37.0
20.0	4.05	40.5	131.0
50.0	17.3	173.0	—

* Two-way

A very simplified explanation of the method of aperture synthesis follows. A platform is moving at constant depth and speed along a straight-line path. Mounted on the platform is a transmit/receive array of hydrophones with identical transmit and receive patterns shaped as illustrated in Fig. 2. As the vehicle traverses its path, an acoustic pulse is emitted every T seconds, and the return echoes are coherently sampled and stored at each range bin. The interpulse period T is equal to the round trip time to the maximum range of interest,

$$\frac{2R_{max}}{c},$$

where c is the sound propagation velocity. As the echo from the last range bin is sampled, the platform has moved a distance equal to its velocity times the interpulse period, or

$$v\left[\frac{2R_{max}}{c}\right]$$

At this new position, another pulse is emitted, and the process repeated. The stored echoes are retained until the platform has travelled a distance equal to the desired synthetic aperture length, L_S. The set of stored echoes resembles the outputs of an array of elements of length L_S with interelement spacing vt. The geometry of the synthetic array is shown in Fig. 3 The beam is now synthesized by coherently summing the stored echoes.

For a given synthetic array length, L_S, the synthetic beamwidth is $\lambda/2L_S$, or one-half that for a real array of the same length. (This improved resolution results because the individual radiators in the synthetic array are sequentially excited, whereas in the real array all elements radiate simultaneously.)

The length of the real transmit array should be no more than twice the desired azimuth resolution. This ensures that the beamwidth of the real transmit array is wide enough to illuminate a target over the entire length of the synthetic array.

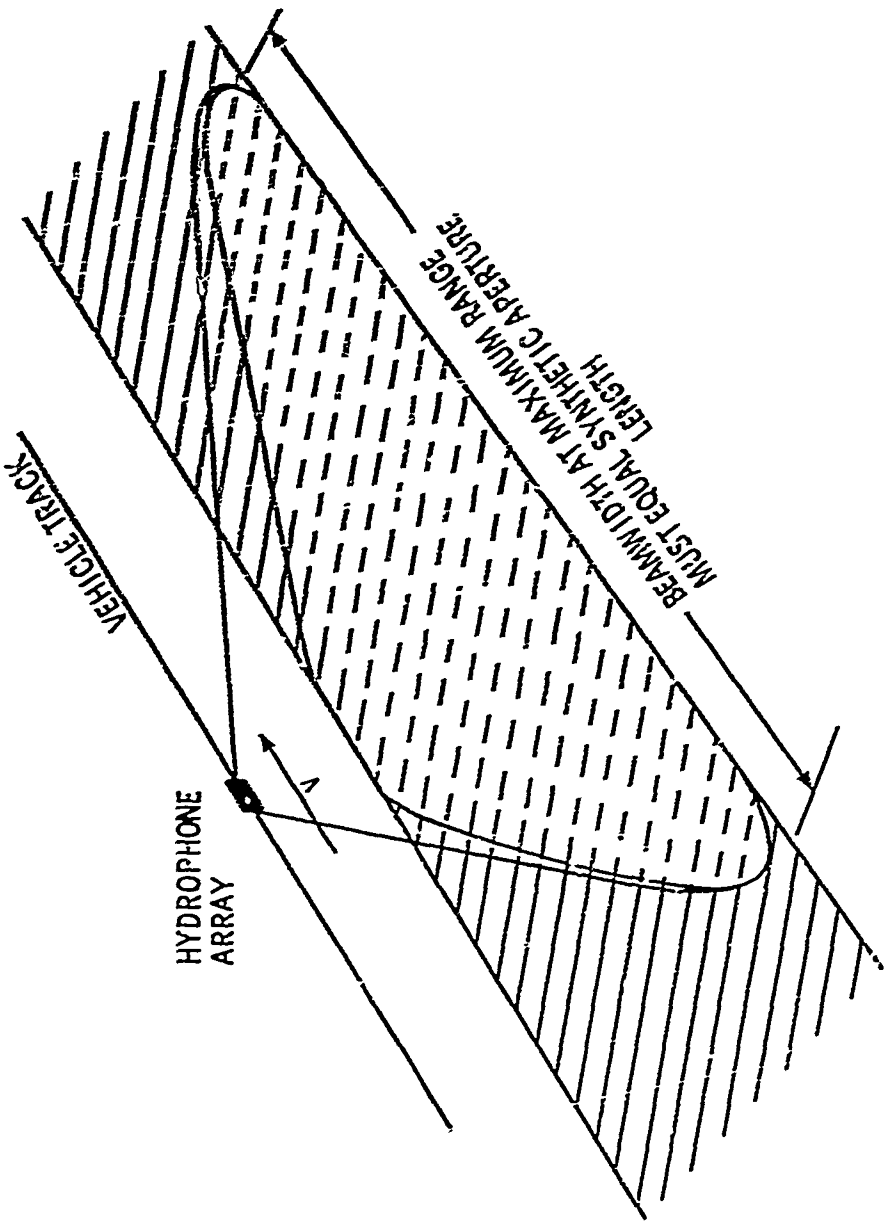

FIGURE 2 TRANSMIT/RECEIVE BEAM PATTERN
OF REAL HYDROPHONE ARRAY

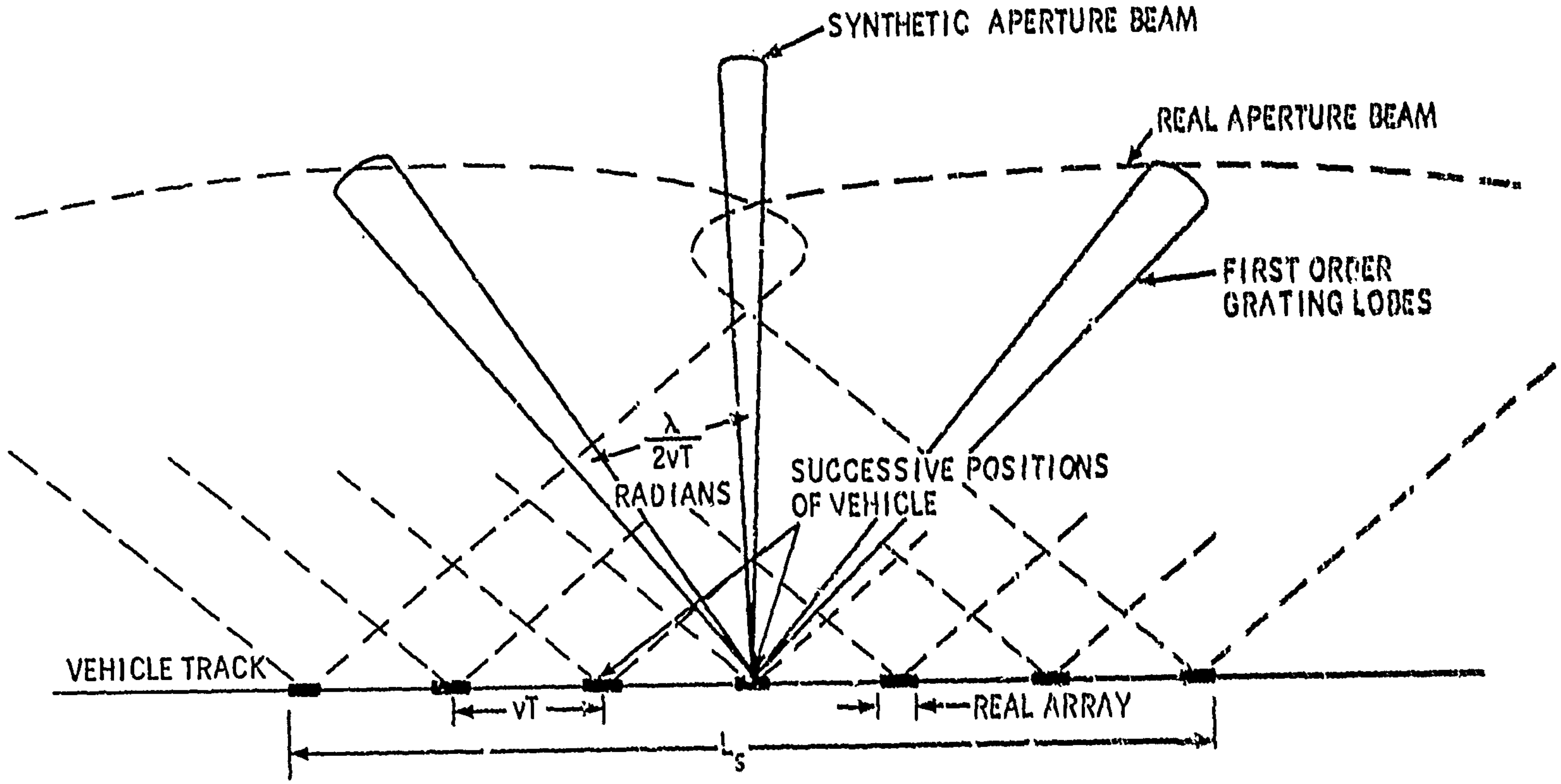

FIGURE 3 PLAN VIEW OF SYNTHETIC APERTURE GEOMETRY; WITHOUT FILLING

Implementation of a synthetic aperture sonar system is further complicated by two effects:

1. Because of the relatively low speed of sound, the platform travels an appreciable distance in an interpulse period. This results in a "thinned" synthetic array, one in which the interelement spacings are many wavelengths. As a result of this "thinness" of the array, second and higher order grating lobes (undesired sidelobe responses equal in magnitude to the mainlobe) appear in the synthetic array pattern. These are illustrated in Fig. 3. One way to eliminate these grating lobes is to fill the along-track distance between successive pulses with a linear array of receive only hydrophone subarrays (see Fig. 4). The resultant array pattern is then the product of the patterns of the thin synthetic transmit array and of the filled synthetic receive array. In order that the grating lobes of the transmit array pattern be cancelled, the synthetic receive array pattern should have nulls at the locations of the grating lobes. If the length of the real receive array is twice the distance travelled by the platform in an interpulse period, the grating lobes will be properly cancelled (Ref. 4). Figure 5 depicts the operation of a synthetic aperture system with proper real receive array length.

2. In the seabed surveillance problem, most targets of interest will be in the Fresnel zone of the synthetic array. This complicates the required processing in two ways. First, a given target is not at the same range from all elements in the synthetic array so that echoes from a given target will appear in different range bins, determined by the position of the pulse in the synthetic array. Second, quadratic phase corrections will have to be applied to the data in order to focus the synthetic array. These problems add to the complexity of the signal processing.

One final complexity required of the processor in any synthetic aperture system is the ability to add phase corrections to the stored data to compensate for deviations the platform takes from its nominal speed and path. An accurate inertial reference is therefore required to measure these deviations.

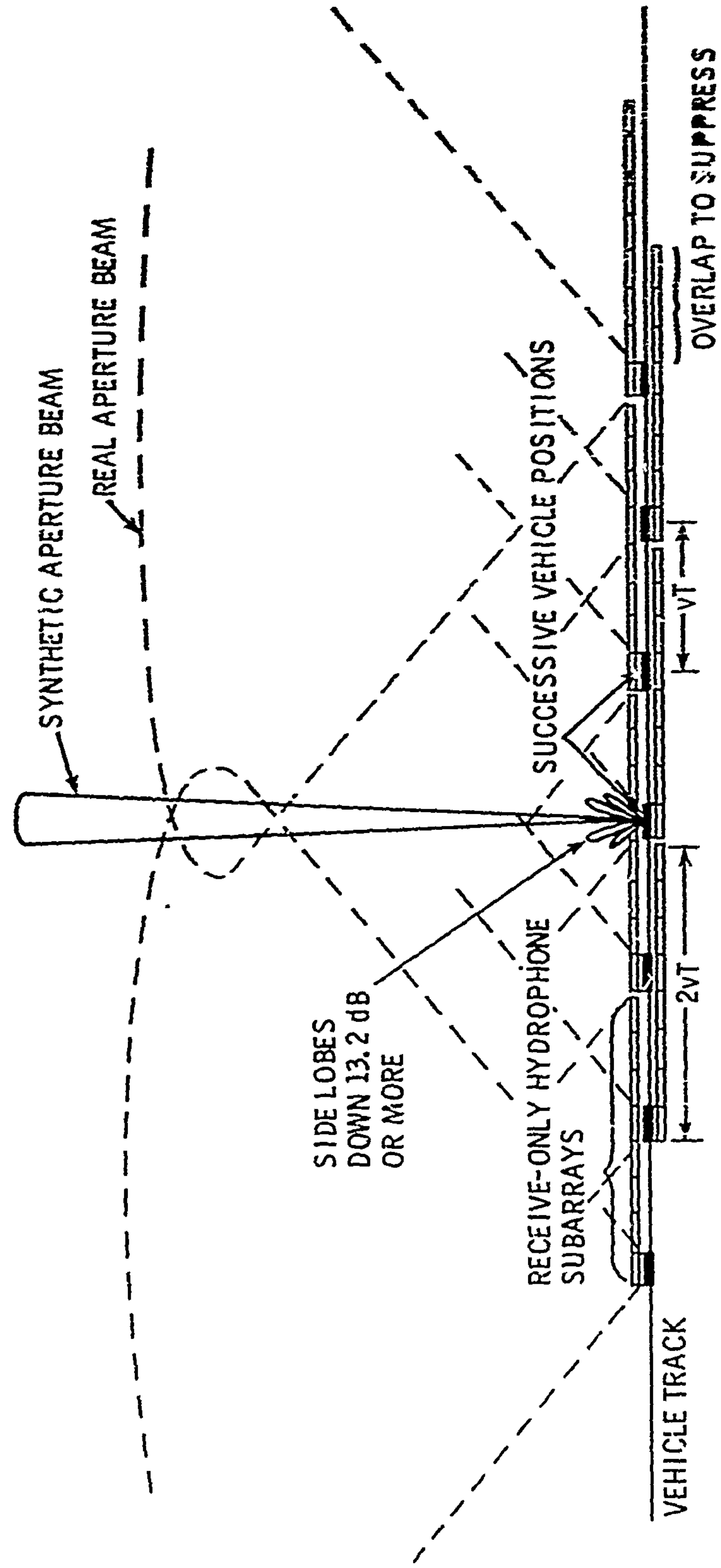

FIGURE 4 PLAN VIEW OF SYNTHETIC APERTURE GEOMETRY; WITH FILLING

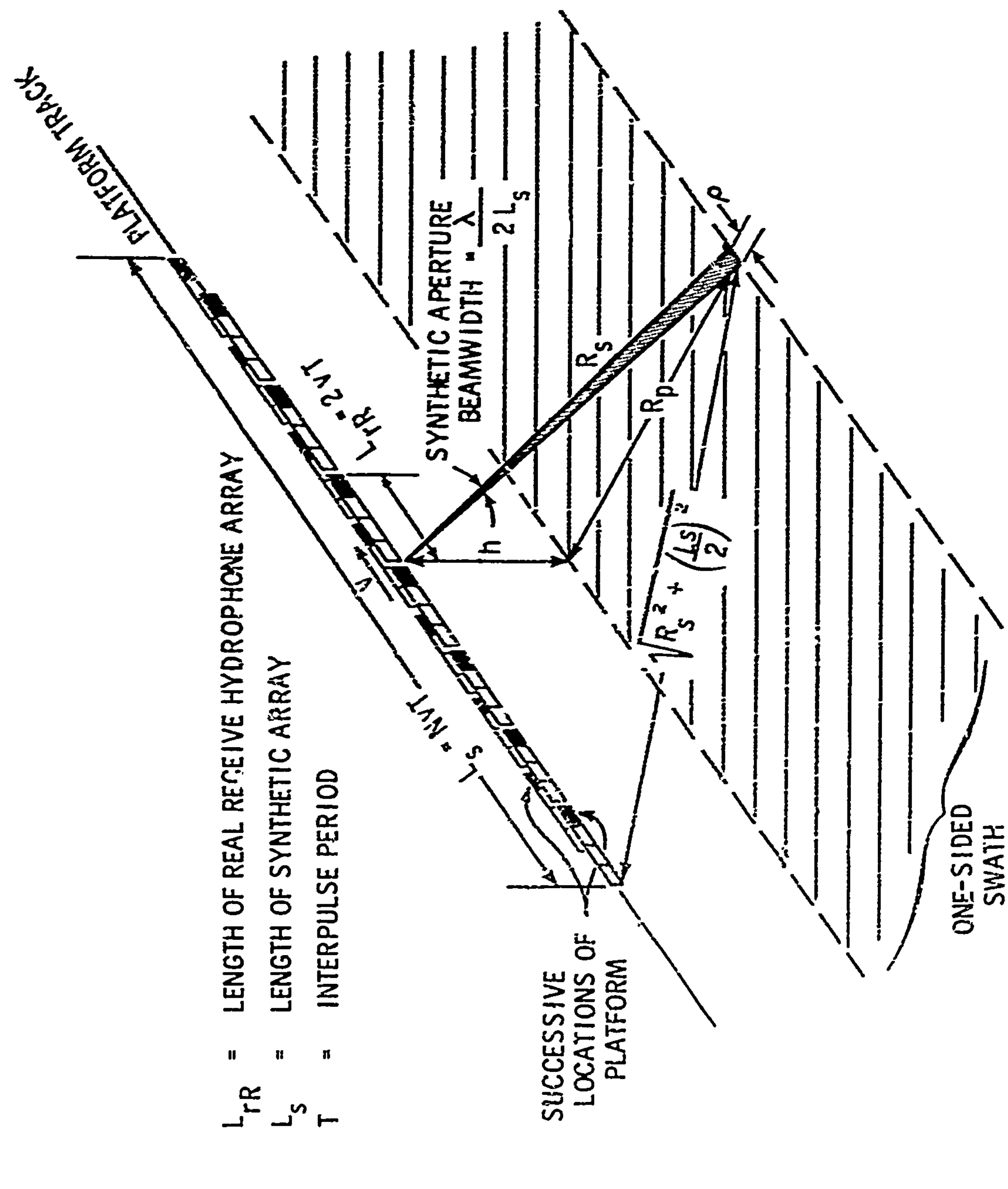

FIGURE 5 SYNTHETIC ARRAY MAPPING SYSTEM

2. SYSTEM TRADEOFFS FOR REAL AND SYNTHETIC APERTURE SYSTEMS

In this section we shall explore parametrically the coverage rate and resolution capabilities of acoustic imaging systems. We shall do this for both real and synthetic aperture systems, after which we shall compare the two. Comparison will yield tradeoff curves that indicate the parameter break points at which synthetic aperture systems are to be desired over real aperture systems.

An acoustic imaging system, whether real or synthetic, achieves a coverage rate A_t determined by the velocity of the platform (carrying the energy source) and the maximum broadside range from which it receives useful returns:

$$A_t = vR_p \text{ per side.} \qquad (1)$$

R_p is the projection onto the ocean floor of the maximum slant range, R_s. These two ranges and the depth of the water below the platform, h, are related by:

$$R_s^2 = h^2+R_p^2. \qquad (2)$$

Thus,

$$A_t = v\sqrt{R_s^2-h^2}. \qquad (3)$$

For a given platform velocity, v, and depth, h, the coverage, A_t, is maximized by finding that system with the greatest useful R_s.

REAL APERTURE MAPPING SYSTEMS

For a real aperture mapping system, the maximum slant range must be constrained by the desired azimuth resolution, ρ, and the diffraction-limited beamwidth of the physical aperture, λ/L_R:

$$R_S \le \rho\bigg/\left(\frac{\lambda}{L_R}\right) = \frac{\rho L_R f}{c}, \qquad (4)$$

where f is the acoustic frequency, λ the acoustic wavelength, c the speed of sound in water, and L_R the length of the physical aperture. Thus, at a water depth h,

$$A_t = v\sqrt{R_s{}^2-h^2} \leq \frac{\rho v f}{c} \; L_R\sqrt{1-\left\{\frac{ch}{f\rho L_R}\right\}^2} \quad \text{per side.} \qquad (5)$$

The aperture must move no more than one aperture length during an interpulse period T or "holes" will appear in the coverage. Thus,

$$vT \leq L_R. \qquad (6)$$

Since T must be at least the round-trip propagation time for a target at maximum slant range:

$$T \geq \frac{2R_s}{c}, \qquad (7)$$

and we have from Eqs. (6) and (7) another constraint on R_s:

$$R_s \leq \frac{cL_R}{2v}, \qquad (8)$$

and, hence, on A_t,

$$A_t = v\sqrt{R_s{}^2-h^2} \leq \frac{cL_R}{2}\sqrt{1-\left\{\frac{2vh}{cL_R}\right\}^2} \quad \text{per side.} \qquad (9)$$

Absorption effects in the acoustic medium produce an exponential decay in signal power with propagation distance. This effect is described by the attenuation coefficient, $\alpha(F)$:

$$\alpha(F) = 1.09\left\{\frac{0.1F^2}{1+F^2} + \frac{40F^2}{4100+F^2} + 0.000275F^2\right\}\text{dB/km}, \qquad (10)$$

where F is the acoustic carrier frequency expressed in kilohertz. If a_o is the maximum tolerable path loss expressed in decibels, then another constraint on R_s and A_t is:

$$R_s \leq \frac{a_o}{2\alpha(F)}, \tag{11}$$

and

$$A_t = v\sqrt{R_s{}^2 - h^2} \leq \frac{va_o}{2\alpha(F)}\sqrt{1 - \left\{\frac{2\alpha(F)h}{a_o}\right\}^2} \quad \text{per side.} \tag{12}$$

For a given set of parameters ρ, v, f, a_o, h, and L_R, the minimum value of the three upper bounds on A_t of Eqs. (5), (9), and (12) determines the maximum coverage rate for a real aperture system. Furthermore, for any ρ, v, a_o, h, and L_R, an optimum acoustic frequency f can be found that maximizes the minimum value of the three bounds. This optimization is easily done (in an analytical sense only; in the hardware world, one may be constrained to use other than the optimum frequency, giving a lower coverage rate). A resulting set of curves of maximum coverage rate at optimum frequency versus real aperture length is shown in Figs. 6 and 7.

SYNTHETIC APERTURE MAPPING SYSTEMS

For a synthetic aperture of length L_s, the angular resolution is $\lambda/2L_s$. Thus, to achieve an azimuthal resolution ρ at the maximum slant range R_s, we must have:

$$\frac{\lambda R_s}{2L_s} \leq \rho. \tag{13}$$

The interpulse period, T, must be at least the round trip propagation time from the end of the synthetic array to a target at maximum slant range, R_s, broadside to the array. That is,

$$T \geq \frac{2}{c}\sqrt{R_s{}^2 + \left\{\frac{L_s}{2}\right\}^2} \tag{14}$$

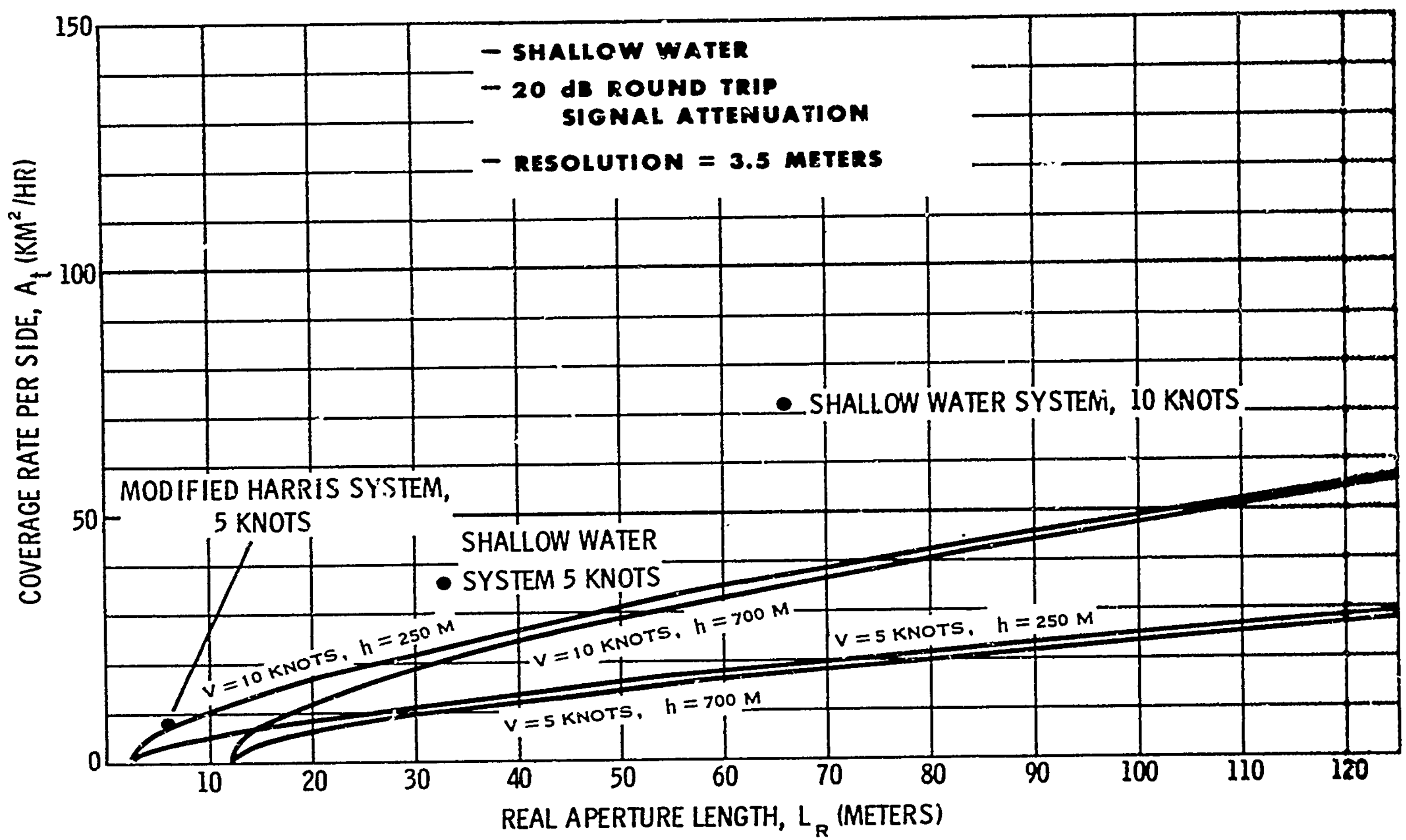

FIGURE 6 REAL APERTURE COVERAGE RATE LIMITS (SHALLOW WATER, RESOLUTION = 3.5 METERS)

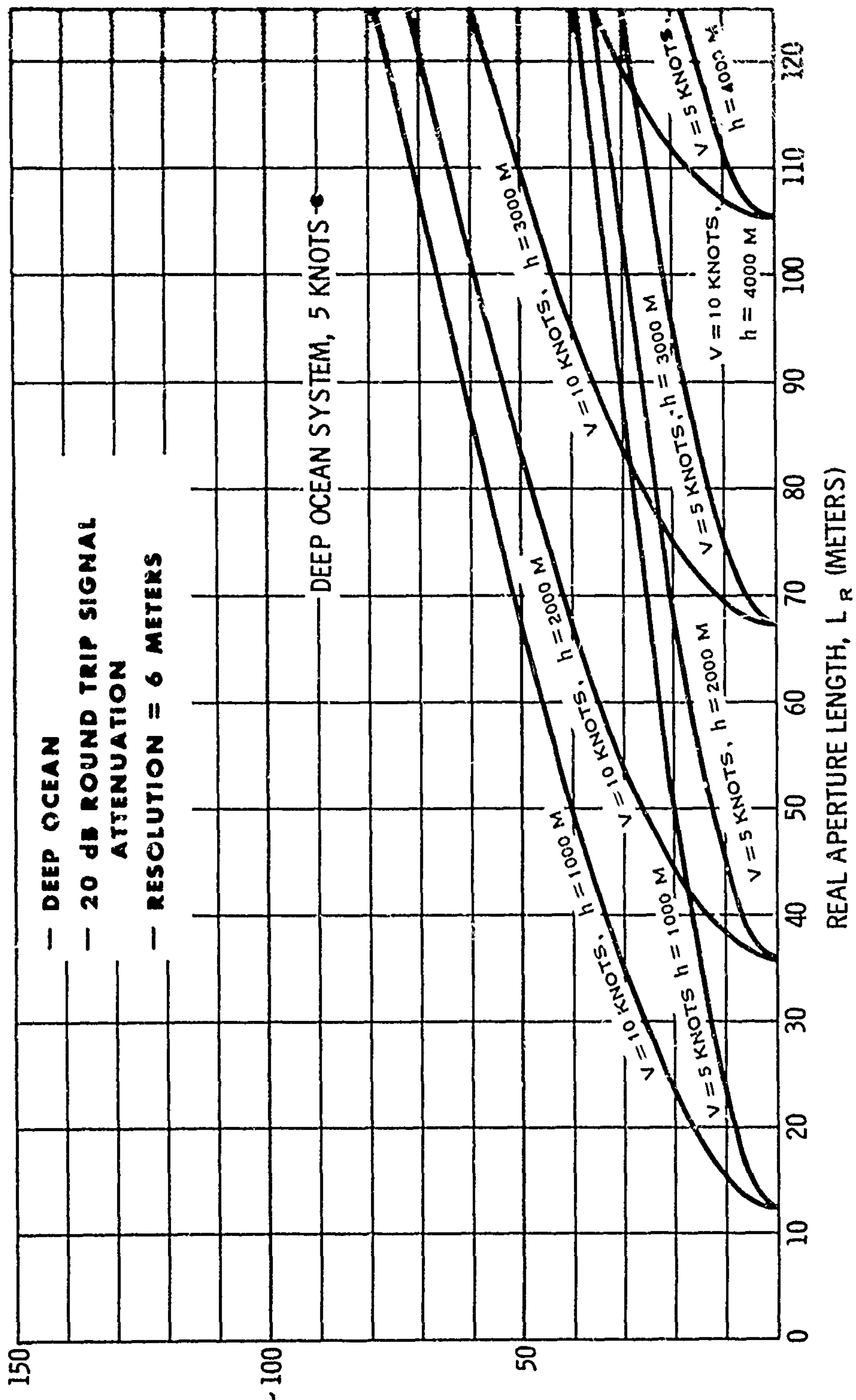

FIGURE 7 REAL APERTURE COVERAGE RATE LIMITS (DEEP OCEAN, RESOLUTION = 6 METERS)

Using Eq. (13) to eliminate L_s from Eq. (14), we obtain an upper-bound value of R_s of:

$$R_s \le \frac{cT}{2}\left[1+\left(\frac{\lambda}{4\rho}\right)^2\right]^{-1/2} . \tag{15}$$

To suppress grating lobes in the synthetic array pattern, the real receive array length, L_{rR}, must be twice the distance travelled by the platform in an interpulse period,

$$L_{rR} = 2vT. \tag{16}$$

This equation allows us to eliminate T from Eq. (15):

$$R_s \le \frac{cL_{rR}}{4V}\left[1+\left(\frac{\lambda}{4\rho}\right)^2\right]^{-1/2} \tag{17}$$

Thus we have a bound on A_t:

$$A_t = vR_p = v\sqrt{R_s^2-h^2} \le v\left[\frac{\left\{\frac{cL_{rR}}{4v}\right\}^2}{1+\frac{\lambda}{4\rho}^2} -h^2\right]^{1/2} \text{ per side.} \tag{18}$$

Attenuation caused by absorption effects limits the maximum range in a manner similar to the real aperture system, although the attenuation limit, a_o, in this case must not be exceeded at the end points of the synthetic array for a target at maximum slant range, R_s, broadside to the array. Thus,

$$\sqrt{R_s + \left\{\frac{L_s}{2}\right\}^2} \le \frac{a_o}{2\alpha(F)}, \tag{19}$$

where $\alpha(F)$ is given by Eq. (10). Eliminating L_s from Eq. (19) by using Eq. (13), we obtain another bound on R_s:

$$R_s \le \frac{a_o}{2\alpha(F)}\left[1+\left(\frac{\lambda}{4\rho}\right)^2\right]^{-1/2} = \frac{a_o}{2\alpha(F)}\left[1+\left(\frac{c}{4\rho f}\right)^2\right]^{-1/2} \tag{20}$$

The corresponding bound on A_t is :

$$A_t = vR_p = v\sqrt{R_s^{\,2}-h^2} \leq v\left[\frac{\left(\frac{a_o}{2\alpha(F)}\right)^2}{1+\left(\frac{c}{4\rho f}\right)^2} - h^2\right]^{-1/2} \quad \text{per side.} \quad (21)$$

For a given set of parameters ρ, v, f, a_o, h, and L_{rR}, the minimum value of the two upper bounds on A_t of Eqs. (18) and (21) determines the maximum coverage rate of a synthetic aperture system. As in the real aperture case, the frequency f can be optimized for each particular set of values of ρ, v, a_o, h, and L_{rR} to maximize the minimum value of the two bounds. This optimization results in a set of curves of maximum coverage rate at optimum frequency versus real receive aperture length. A set of such curves is shown in Figs. 8 and 9.

COMPARISON OF THE SYSTEMS

To understand the necessity for a synthetic aperture approach at large coverage rates, one need only examine the coverage limits of Figs. 6 to 9. It is seen from the curves that, for shallow depths and very low coverage rates, real aperture systems accomplish the required coverage with shorter aperture lengths, while at higher coverage rates, synthetic apertures require much smaller real apertures. The actual break point between the two systems is a function of ρ, v, h, and a_o.

The loci of the break points are plotted in Figs. 10 and 11 for several combinations of velocity, depth, and attenuation limit. These loci divide the (A_t, ρ) plane into two regions: (a) in the region above and to the left of a given locus a synthetic aperture system can map at the required coverage rate and resolution with a shorter physical aperture length than a real aperture system requires; (b) in the region below and to the right of the given locus, a real aperture mapping system requires a shorter physical aperture length. It should be emphasized that these tradeoff curves have been drawn with physical aperture length minimization in mind. The processor complexity necessary for synthetic aperture synthesis is considerably greater than that for the real aperture case.

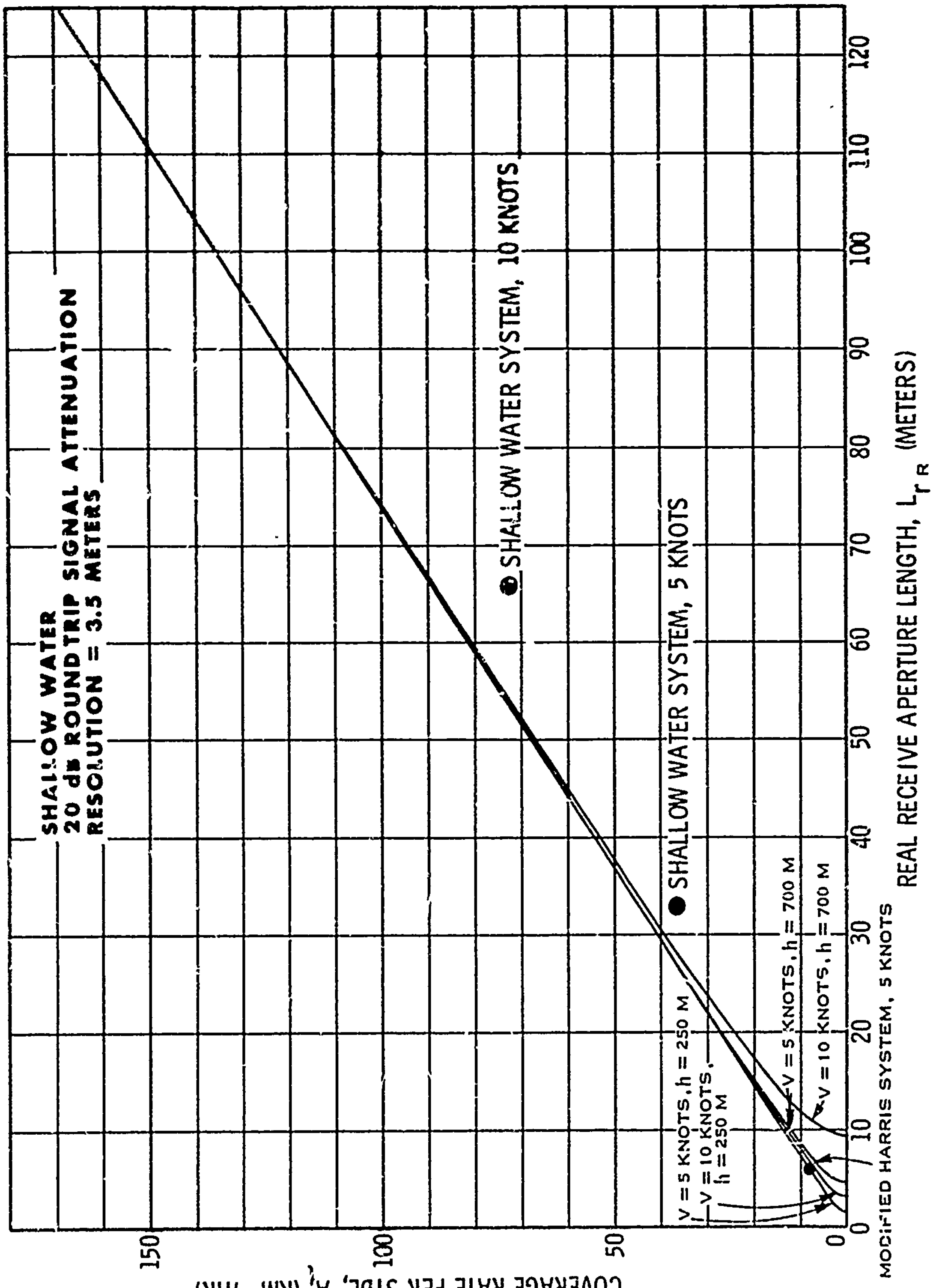

FIGURE 8 SYNTHETIC APERTURE COVERAGE RATE LIMITS (SHALLOW WATER, RESOLUTION = 3.5 METERS)

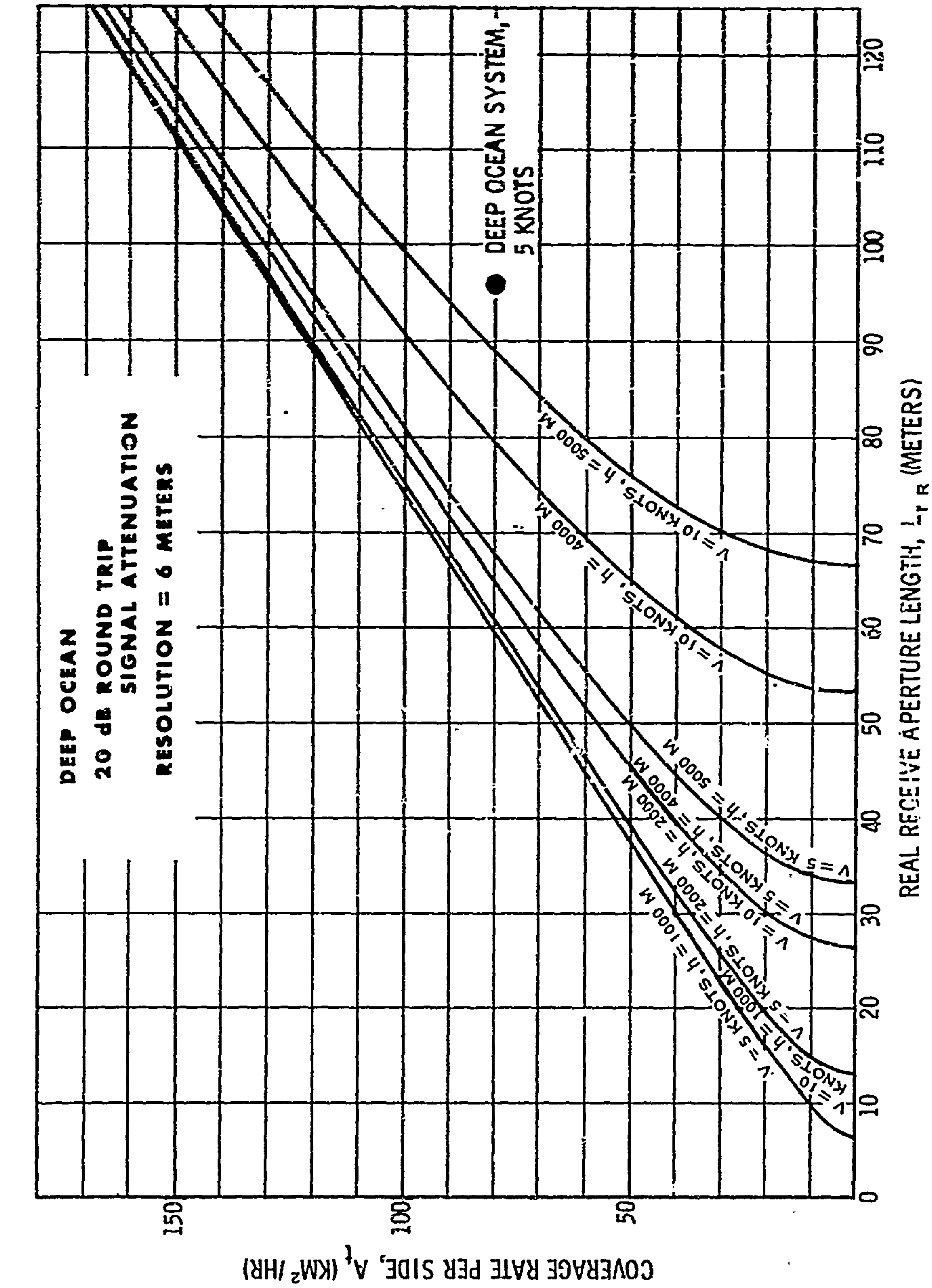

FIGURE 9 SYNTHETIC APERTURE COVERAGE RATE LIMITS (DEEP OCEAN, RESOLUTION = 6 METERS)

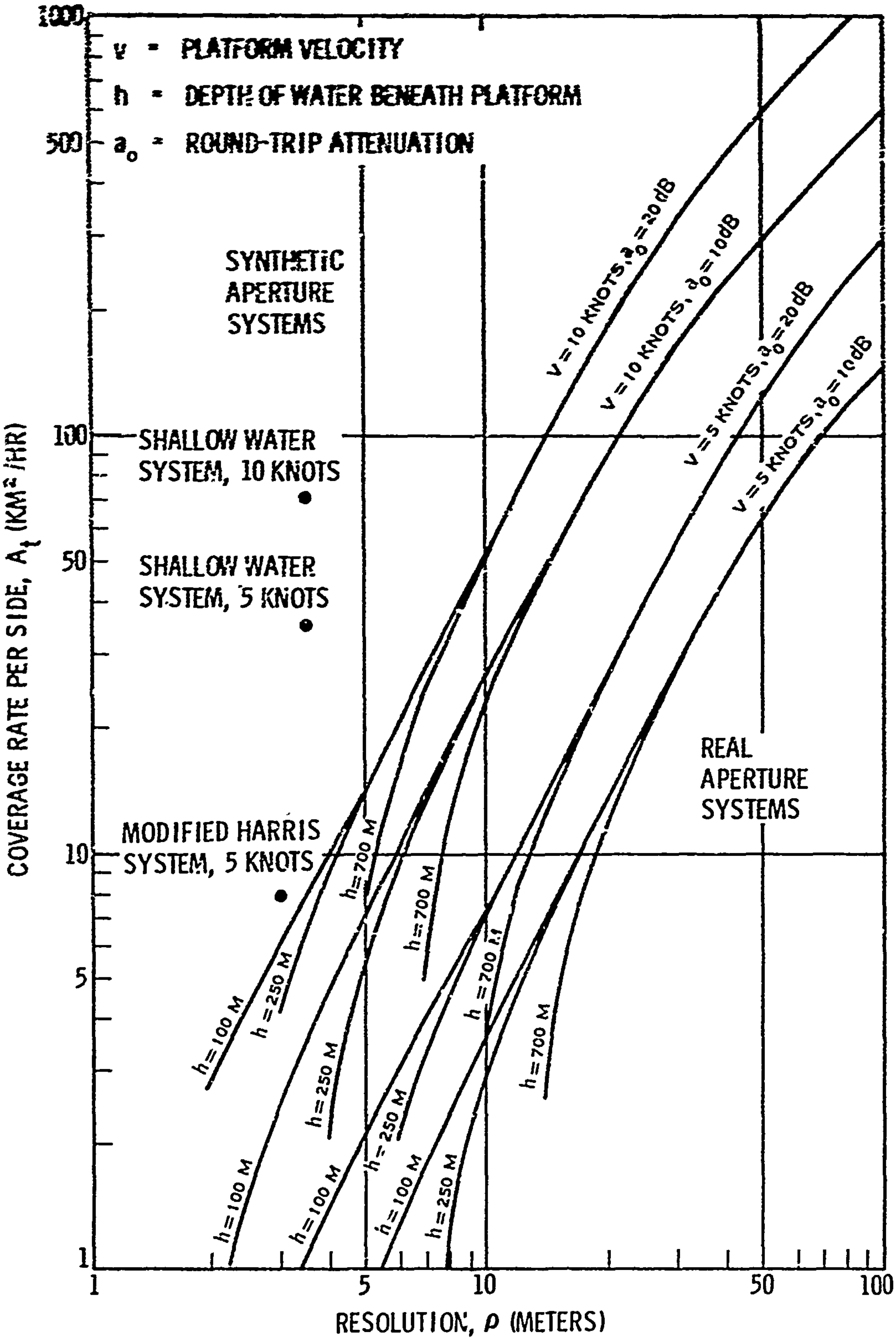

FIGURE 10 SYSTEM TRADEOFFS - SHALLOW DEPTHS

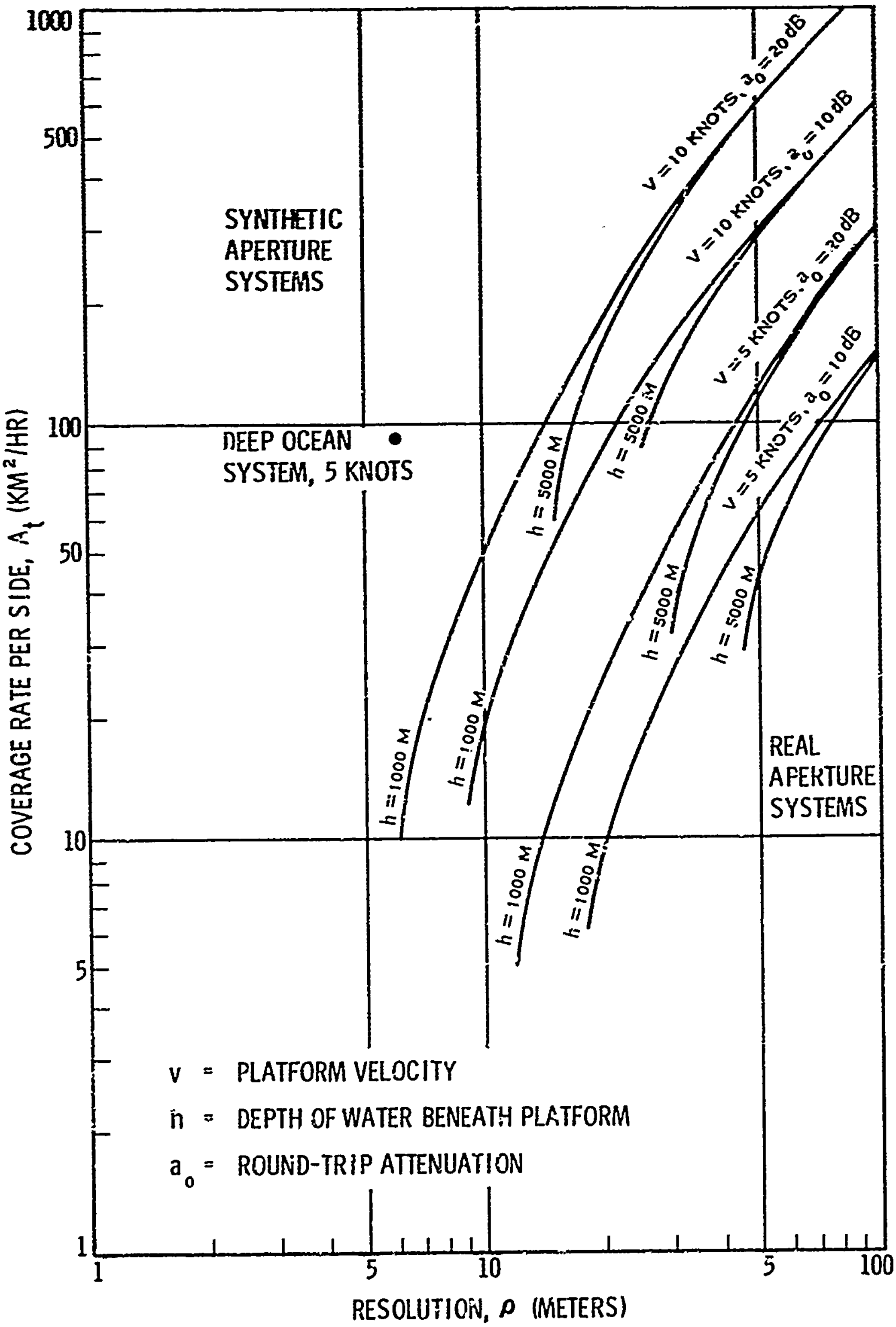

FIGURE 11 SYSTEM TRADEOFFS - DEEP OCEAN DEPTHS

Thus, for system requirements in the vicinity of the trade-off curves of Figs. 10 and 11, special consideration should be given to the relative merits of short physical aperture lengths and simple processors. In many cases it may be prudent to settle for a longer physical aperture length for the sake of a simpler processor.

Also plotted in Figs. 10 and 11 are the operating points of the four specific synthetic aperture systems to be discussed in Section 3.

3. SCHEDULE AND COST ESTIMATES

In light of the system capabilities determined in Section 2 and the operational requirements of a Seabed Treaty policing system briefly considered in Section 1, three synthetic aperture surveillance systems are postulated in this section. Order-of-magnitude development and production cost estimates and approximate development times are included for each. In addition, the costs and development times of a suitable feasibility demonstration system are estimated. It should be emphasized that all cost and development time estimates in this paper are, at best, educated guesses and are not to be construed as anything more than order-of-magnitude guides.

All the systems discussed in this section have been plotted on the system coverage limit curves of Figs. 6 to 9 and on the system tradeoff curves of Figs. 10 and 11.

SUGGESTED SYSTEMS

Shallow Water Systems

To monitor continental shelves or other shallow water areas, two alternative synthetic aperture systems are suggested that are capable of two-sided mapping at coverage rates of 72 and 144 km^2/h. The slower system travels at 5 knots and processes 200 seconds of data to form the synthetic aperture. The faster system travels at 10 knots, requiring half the processing time but twice the real array length of receive hydrophones. Both systems achieve 3.5-meter azimuth resolution at a maximum range of 5 km and operate with a 3-kHz acoustic carrier frequency. This choice of carrier frequency is not rigid but was chosen for its low attenuation coefficient and because sonar hardware exist that operate at this frequency.

Deep Ocean System

For monitoring deep ocean depths, a 6-meter resolu-

tion system is suggested. The platform travels at 5 knots and processes 320 seconds of data. Its maximum range of 16 km give the system a two-sided coverage rate of 180 km^2/h.

Feasibility Demonstration System

A very low coverage rate system is suitable for demonstration of the feasibility of synthetic aperture acoustic mapping systems. The demonstration system could be fabricated from the modified Harris, Model 853, Narrow Beam Echo Sounder described in Section 4, operating at an acoustic carrier frequency of 12 kHz. The system would provide a 16 km^2/h two-sided coverage rate with a 3-meter resolution at 900 meters maximum range.

DEVELOPMENT SCHEDULE AND COSTS

Preliminary to assembly of a demonstration system, measurements should be made to determine medium stability. This experiment, which is described in Section 4, should take from 9 to 12 months to complete and cost from $100 000 to $150 000, including data reduction.

Following completion of this experiment, a demonstration system can be assembled from the Harris equipment, a multichannel tape recorder, and land-based data processing. This program, including test, could be completed in 1 year. Specifications for a seagoing prototype could be completed in another 3 months and the prototype system assembled from existing parts in another 18 months. Thus, assuming funding levels shown in Table 2, a working prototype could be available within 3-1/2 years after initial experiments.

PRODUCTION COSTS

Estimates of mapping system production costs, based on production quantities of five units, are presented in Table 3. Cost estimates are presented in this table for the systems discussed in this section, in one case for both a one- and two-sided coverage system.

Table 2
Development Schedule and Costs - Exclusive of Platform

	Yearly Quarters													
Schedule	1	2	3	4	5	6	7	8	9	10	11	12	13	14
A. Ocean Stability														
1. Tests														
2. Data reduce														
B. Demonstration System (using modified Harris Narrow Beam Echo Sounder)														
1. Assemble														
2. Test														
3. Data display and analysis														
C. Prototype														
1. Write specifications for 5-km system														
2. Construct and lab test														
3. Tests at sea														
Costs	$120K		$600K				$2000K				$2500K			

Table 3

Mapping System Production Cost Estimates

(Per-System Cost Estimates Based on Production Quantities of 5 Units)

	Shallow Water			Deep Water	
	Normal Speed		High Speed		
Resolution (m)	3.5	3.5	3.5	6	6
Coverage Rate (km^2/h)	36*	72**	144**	90*	180**
Receive Array Length (m)	33	33	66	107	107
A. Arrays and Hydrophones (Installed)	$ 40	$ 60	$ 80	$120	$180
B. Projector	40	50	60	50	70
C. Inertial Platform	60	60	80	80	80
D. Storage, Process, and Display	120	180	270	140	200
E. Spares and Documentation	40	50	60	60	70
Installed Cost (Thousands)	$300	$400	$550	$450	$600

* One-sided

** Two-sided

4. CRITICAL AREAS AND FEASIBILITY DEMONSTRATION

CRITICAL AREAS

Synthetic aperture mapping systems achieve their high coverage rates by coherently processing acoustic echoes received over long periods of time, over long spatial separations along the vehicle track, and from long slant ranges. The following areas are therefore critical to their success as mapping systems.

Medium Stability

The most crucial issue is that of medium stability. The ocean is a turbulent medium. There exist within it random inhomogeneities constantly undergoing turbulent mixing. This mixing of "patches" of water at varying temperatures gives rise to a random thermal microstructure within the sea that varies with time.

Acoustically, the effect of this microstructure is to produce a random spatial and temporal variation in the phase and amplitude of an acoustic wavefront that has propagated through the turbulent region. Because the velocity of sound is determined by, among other things, the temperature of the water, the time of arrival of an acoustic ray that has propagated through many patches of varying temperatures varies randomly about a mean value. This causes a random phase component in an acoustic carrier frequency. In addition, the turbulent patches act like acoustic lenses on a wavefront with spatial extent, causing random focusing and defocusing of the wavefront. The most turbulent regions of the ocean are at the surface, along the boundary of stratification of water density due to severe thermoclines, and in boundary regions between the general ocean and strong ocean currents. The first two of these can be avoided by transiting the real aperture at such a depth that it is normally below them. This can be done either by placing the system on a submarine or towing the array underwater. In either case, the data stabilization system requirements are simpler since these are both quieter platforms.

Clearly, the performance of the synthetic aperture imaging sonar, which relies particularly on phase coherence between successive synthetic aperture elements, is potentially limited by the medium instabilities well

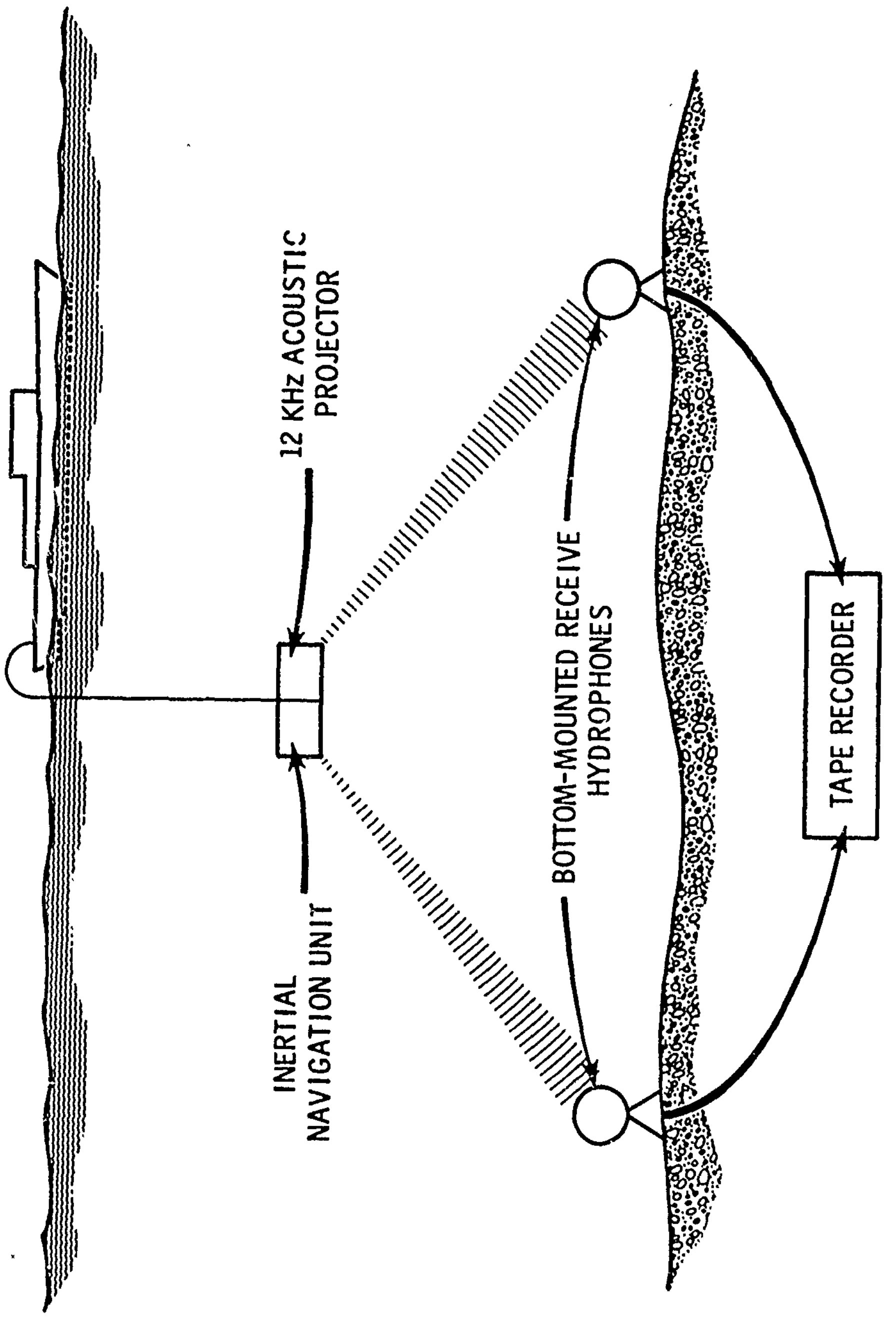

FIGURE 12 PROPOSED MEDIUM STABILITY EXPERIMENT

periment, followed by laboratory checkout of the experimental apparatus and data reduction algorithms in a controlled environment, and finally the measurements themselves. This experiment should take from 9 to 12 months to complete and cost from \$100 000 to \$150 000, including data reduction.

A mention of the state-of-the-art of towing arrays behind a ship or submarine is appropriate here. There is considerable effort in this field of technology today, and it will probably change drastically in the near future.

Data Processing

The storage of raw data and subsequent formation of the synthetic aperture image requires a data storage and processor of moderate complexity. A fairly detailed look has been taken at the structure of the processor required to implement the shallow-water normal-speed system discussed in Table 2 (Ref. 6). A brief review of the system follows.

A platform consists of a 5-meter long transmitter array and a 64-element, 33-meter long linear receive array. A burst of a carrier frequency (5 ms of 3 kHz) is transmitted at time intervals corresponding to the time it takes the receive array to travel half its length (6.6 s). The receive elements are connected so as to form eight subarrays of approximately 4-meter length apiece, each having a broadside beamwidth of ~0.12 radian. Outputs of the subarrays are demodulated, sampled every 5 ms, digitized, and stored into a core memory. One-thousand returns, corresponding to as many range bins, from each pulse transmitted and each of the eight subarrays are stored in a sector of the memory. Subsequent received sets for other transmit pulses are stored in memory sectors so that, as the 32nd set is being received, the previous 31 sets are available for synthetic aperture beamforming.

The processing is done in three basic steps:

1. Returns from a given area of ocean floor (essentially from an area of 4 x 33 meters) are recalled from the memory.

2. Phase corrections, for geometric and timing considerations, are applied to each return.

3. A broadside beam, located at the center of the synthetic array, plus adjacent beams on either side of center are formed to resolve the 4 x 33 meter area into eight resolution cells of approximately 4 x 4 meters. Steps 1, 2, and 3 are repeated for each range bin. The imaging is achieved after the ship has transited the area; consequently, the image formed is one-half the length of the synthetic aperture behind the position of the real array.

A preliminary block diagram of the system is shown in Fig. 13. The numbered areas are described below:

1. The 64 hydrophones are arranged in subgroups of eight adjacent hydrophones each. Outputs of all hydrophones in a subgroup are summed (analog) to form overlapping broadside beams.

2. Outputs of each beam are demodulated into inphase (I) and quadrature (Q) channels. The bipolar outputs are then low-pass filtered (200 Hz) and sent to a sample-and-hold circuit. The sampling time (as well as the transmit time) can be varied to allow for platform drifts, i.e., deviations from baseline. The outputs of the sample-and-hold circuits are multiplexed and digitized at a 3200 Hz conversion rate.

3. The memory must store 1000 (or 1024) range gated returns from each transmit pulse for each of eight beams for a total of 16 000 eight-bit words. A total of 32 of these "T_x sets" must be stored, requiring a memory of 4×10^6 bits with a probable format of 128 000 words x 32 bits per word. Memory write cycles should have priority over memory read cycles to prevent a buildup of data between the A/D converter and memory.

4. Memory addresses for readout must reflect the parabolic range correction factors. This can be done by using the perpendicular range as a base address and

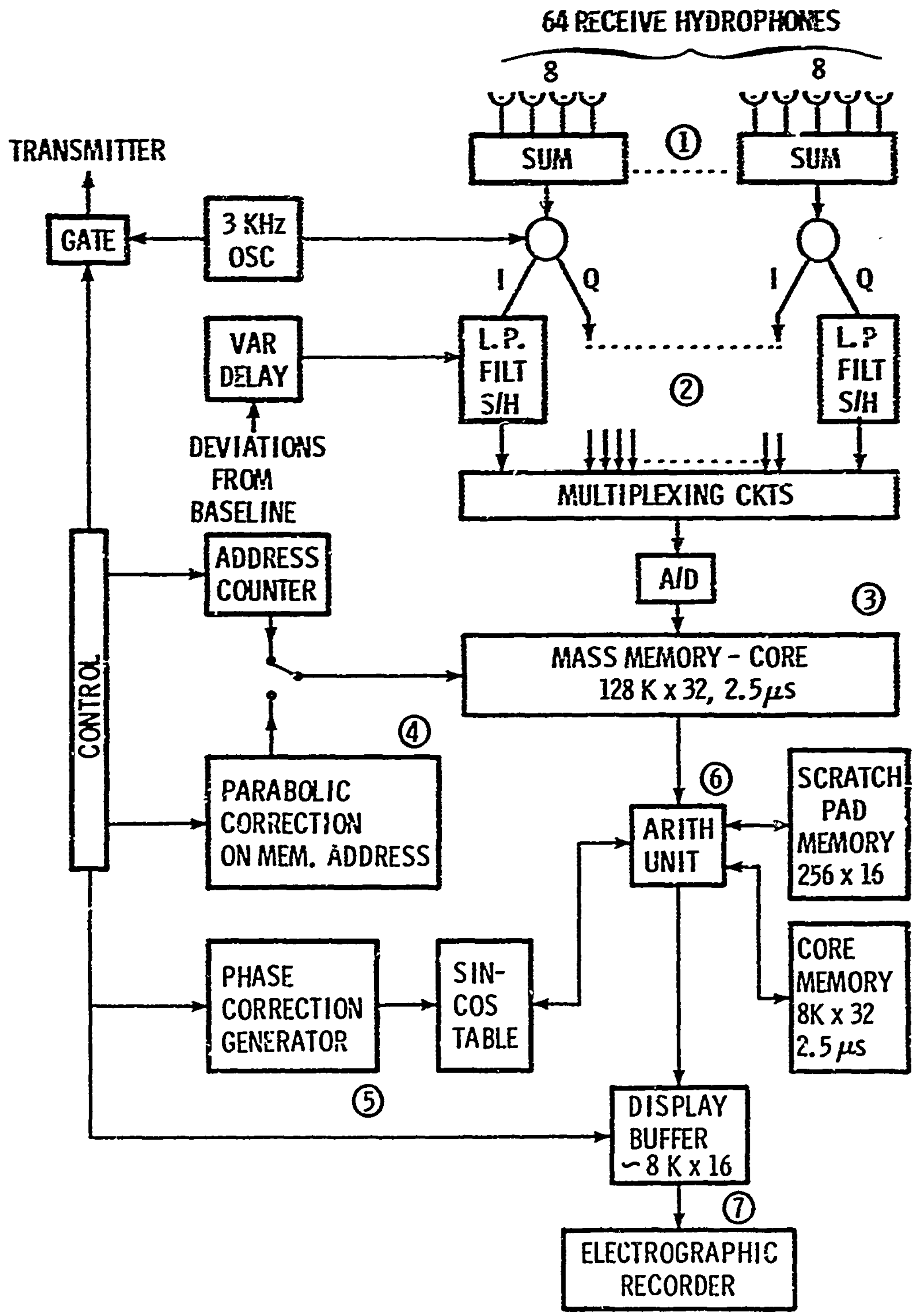

FIGURE 13 BLOCK DIAGRAM SYNTHETIC APERTURE SONAR PROCESSOR

adding correction factors that are a function of T_x set number and range.

5. Parabolic phase corrections are required to obtain a coherent set of data for a given range. As data are extracted from memory, phase corrections are fed into the arithmetic unit. Since the phase function is continuous with respect to the subbeam position, phase corrections can be generated or calculated from prestored plus interpolation constant data. This would yield an angle that would address a sine-cosine table. The sine-cosine table is also used for rotations required for forming the fillin beams. As the raw data are extracted from the main memory, the corresponding phase corrections are applied to the data prior to its storage in a small relatively high-speed memory.

6. The processing to be done on the now coherent set of data, u_x, to obtain along-the-axis cells, U_b, is:

$$U_b \doteq \sum_{x=-63}^{+64} u_x \exp i\,(-2\pi kb/128y),$$

where b = beam position relative to center of synthetic aperture data set = -3, -2 ... +4,

y = perpendicular range,

x = subarray spatial beam position index relative to center of array (128 nonoverlapping data points),

k/y = beam shifting factor so that along-the-track resolution cell positions remain constant with perpendicular range.

The above equation must be solved for all perpendicular ranges between transmit pulses. Also, it should be noted that each T_x processing cycle produces overlapping fine beams, covering identical spatial positions but from a different-by-one set of T_x returns. These are combined coherently, thereby requiring additional memory storage of approximately 4k x 32 bits.

7. For processing efficiency the output of the processing unit is a series of seven "x" (along the

platform track) resolution elements for every step in "y" (perpendicular to platform track). The required format for the electrographic recorder requires a stepping through all points in y for every step in x. This reformatting, as well as system-to-recorder synchronization, requires the use of a buffer. The minimum size of this buffer is 8k x 16 bits.

Target Recognition and Identification

Acoustic imagery is essentially analogous to radar imagery, and the potential of high resolution acoustic systems is probably best illustrated by current synthetic aperture radar maps. The radar photographs are almost comparable to optical photographs. Acoustic imagery should be capable of approaching the resolution of radar photographs.

Interpretation of the acoustic imagery and the recognition and identification of targets therein are functions of the relative backscattering properties of the ocean floor and of the targets.

Scattering from the ocean floor is complex in nature and is largely determined by two characteristics: the composition of the floor and the roughness of the area. The composition of the floor may vary from loose mud, with an acoustic impedance close to that of sea water, to hard rock or packed sand, whose impedances are up to 30 times higher than water. Loose mud is essentially transparent to low frequency acoustic waves, allowing considerable penetration, whereas hard rock and packed sand scatter most of the incident energy. Furthermore, the amount of scattering is dependent upon the roughness of the area. When the characteristic size of the bottom irregularities is roughly the same as a wavelength, scattering is enhanced greatly over that of a flat surface of the same composition (Ref. 7). In that the physiographic areas and acoustic domains of much of the world's oceans are known or easily determined, those areas where photointerpretation is going to be difficult because of bottom roughness can be predetermined, as can the opposite case where the terrain is smooth and flat (Ref. 8).

Acoustic backscatter from targets is determined by their size, shape, and acoustic properties. Acoustic backscatter is similar to radar in that different shapes have different scattering properties and these are dependent upon the wavelength of the incident ray and the shape and size of the scatterer. It differs, however, in that the acoustic wave is a longitudinal compression and rarefaction wave, whereas the radar wave is polarized and transverse. The effect of this difference is to simplify the acoustic scattering problem, producing fewer cases to be considered. A considerable body of data exists on the scattering by various geometric shapes of radar energy; however, very little has been done in acoustics. The translation of the radar data to equivalent acoustic wavelengths is possible and should be done. Numerical techniques for solving acoustic scattering of simple and rather complex shapes have been proposed, together with an experimental program for their verification (Ref. 9).

Aside from the size and shape dependencies, acoustic backscatter from metallic or concrete target structures will be in sharp contrast to the surrounding background because of the high acoustic impedance of these target materials (Ref. 10). Furthermore, it may be possible at very low acoustic frequencies for the incident acoustic wave to excite certain mechanical response modes of objects such as submarines, deep submersibles, or cylindrical weapon housings. The excited resonant mode may retransmit energy to the medium, dissipating the stored energy. This may be detected as an individual line response, which would differ from the response of the general background. Whether mechanical resonant modes of structures with shape and size sufficient to store a weapon of mass destruction can be excited and subsequently detected requires considerable analysis and experimental verification. This effort has considerable potential since it provides a possible mechanism for simple detection of high strength pressure vessels whether on the surface of the seabed, buried beneath it, hidden in a cave, or deep in solid rock or sand. The numerical technique for the solution of acoustic scattering problems (Ref. 9) can include limited number of coupled differential equations of the excitable modes of a container made of a specific material and shape; however, empirical techniques are necessary to identify the modes that can be excited.

Finally, a rationale must be developed to describe the character and properties of potential weapons and the containers that might be emplaced on or in the ocean floors.

In summary, the resonant frequency of air-filled, high-stress containers may be detectable against the general background of the sea bottom at rather low acoustic frequencies.

At the frequencies proposed earlier for acoustic imagery, namely, 3.5 to 5 kHz, target identification can only be done as it is with optical or radar imagery, i.e., by looking for changes in the ocean bed and/or the sighting of characteristic shapes and sizes that differ from the normal terrain. Even at the 3.5 to 5 kHz frequency, acoustic imagery affords enough penetration of the bottom of the ocean to see through soft bottoms to hard structures such as would be required to house weapons.

Analysis of acoustic backscatter of various geometric shapes is required, as is analysis of the ability to excite and visualize structural mechanical resonant frequencies.

Precise Navigation at Sea

Navigation at sea differs from that on land (surveying) in two main respects.

1. The navigator's position at sea is continuously changing, and consequently the position now is most likely not what it will be in the immediate future.

2. With adequate knowledge of the geopotential, the distance from the center of the earth to the navigator is accurately known at sea whereas on land topographic information (leveling) is required. As a consequence of these two factors, navigation at sea is roughly as difficult as is surveying on land. The precision of the result is determined by the precision of the data and the precision of the "known" (unknown) constraints: on land, height above sea level; and at sea, ship's motion. Most systems are affected by one or the other (or both).

It is widely recognized that classical celestial navigation is limited in precision not only by the data (angular measurements) but by the availability of the data. A glance at a synoptic weather chart shows that in "most" places "most of the time" it is cloudy; the exception to this statement exists in narrow bands of latitude around the Tropics of Cancer and Capricorn. Even when the data are available, the precision of the data limits the precision of the result to several nautical miles.

We are carefully avoiding the use of the word "accuracy" for a very good reason: the word "accuracy" connotes existence of a standard against which we measure the accuracy of a secondary system. For example, it is reasonable to talk about the accuracy of a length measurement because the meter exists as an unassailable standard of length. No such standard exists for a navigation system, and therefore, we are forced to talk of internal consistency or precision. Once again we have to make a slight exception — there is in the courtyard at the Old Greenwich Observatory a brass strip defined as 0° longitude. The ability of the system to reproduce this 0° longitude might be called its "accuracy" in one coordinate, at one place. (Basic characteristics of any system proposed as an absolute standard are that the system have high precision and be readily available for comparison.)

Of all the navigation systems we know <u>in current existence</u>, the Transit System (U.S. Navy Navigation Satellite System) is the most precise. It does, however, have certain shortcomings and limitations, as do all navigation systems. The Transit System relieves the long-standing problems imposed by the weather on celestial schemes; moreover, it is globally available (unlike LORAN) and is currently being exploited and used by commercial companies, both U.S. and foreign, as well as foreign governments. Its present limitations for at sea usage are that:

1. For utmost precision it requires precise knowledge of the ship's motion while the satellite data are being monitored (roughly 10 minutes). As a rule of thumb, one knot <u>error</u> in the ship's speed causes a 0.2 nmi position error. On the other hand, methods are known that use only computer software to reduce this sensitivity by a factor of 5.

2. Position information is not continuously available. A fix can be obtained on the average of about once every hour — more often near the poles, less often near the equator. Consequently the user must depend on some supplementary system, e.g., dead reckoning, to keep track of his position between fixes. If LORAN is available, differential LORAN measurements should provide a reasonable augmentation of any dead-reckoning scheme. An expensive but effective method of providing interpolation between satellite passes is, of course, an inertial system.*

We have spoken about the limitations of Transit without mentioning its real assets: with a precise knowledge of ship's motion (say, to the nearest 0.1 knot)** it is capable of consistently giving precisions — day in and day out on a worldwide basis — far better than any other operational system. The fix is in a single global coordinate system, making datum ties (coordinate transformations) unnecessary. If one has several passes available at an anchorage, then the user can compute (survey) his position in three-dimensional space, as well as in the traditional latitude and longitude. The equipment to do this is completely automatic and is currently (1970) commercially available from two manufacturers. It is relatively expensive. The computer receiver combinations currently are selling for about $70 000. A receiver with data output equipment (punched paper tape) is available for approximately $50 000. Almost any general-purpose digital computer can be programmed for the navigation computation. Directional antennas are not required. The system has been operating around the clock almost without failure for seven years. There are currently four satellites in orbit.

We have deliberately slighted inertial systems because of their inherent instabilities and expense. It is well known that pure inertial systems possess Schuler instabilities. This is a system resonance that

* Note in Table 3 that an inertial platform is already required to compensate for platform motion.

** LORAN can be used for this purpose.

must be removed (or damped) if reasonable results are to be obtained over long at-sea periods; otherwise, the precision of the fix continuously degrades (in an oscillatory sense) with time. One way to damp these oscillations is to use a hybrid navigation system, e.g., satellite doppler-inertial. Once again, these systems tend to be both complex and expensive.

Among the current inertial systems in operational usage today is the submarine inertial navigation system (SINS) used in the U.S. Navy's Polaris submarine. This is probably the most precise inertial system available; the system is capable of correcting the velocity error, assuming the Schuler instability has been damped and steady state is reached. There are many commercial inertial systems currently available that are less expensive and less precise. The future holds considerable promise for increased precision in inertial and hybrid systems.

The location "accuracies" desired for a craft mapping the ocean bottom are: (a) to be able to designate, after-the-fact, an interesting area for closer examination, and (b) to minimize the overlap required for registry of side-by-side maps. The two-sided ground swath mapped by the synthetic aperture technique ranges from 16 to 20 km. The current satellite navigation system accuracy, together with a current commercial inertial system or LORAN, where available, and together with procedures to minimize velocity errors, appears to be more than adequate for either task. It should be noted that the task of locating an object on the ocean bottom with a high resolution system such as that of the Mizar should be much simpler with the support of the system proposed herein, which in addition to furnishing location position also furnishes a topographic map of the surrounding area.

FEASIBILITY DEMONSTRATION

An early demonstration of a synthetic aperture bottom mapping system could be built around a modified Harris Model 853 Narrow Beam Echo Sounder (Ref. 11). Harris ASW is a Division of the General Instrument Corporation, Westwood, Massachusetts.

The Narrow Beam Echo Sounder is an electronically stabilized narrowbeam depth-sounding system used on the U.S. Coast and Geodetic Survey Ship Surveyor. The equipment is modified to look directly below the ship using a 2-2/3° fore and aft beam and a 54° athwart ship beam. A separate broad (20°) receive beam is used, and it, together with the transmit beam, is electronically stabilized with respect to the local vertical supplied by a vertical gyro. The system is used for accurate bottom profiling. The transmit and receive array have the following parameters:

L_T = Transmit aperture length = 3 m

L_R = Receive aperture length = 3 m

N_T = No. elements, transmit = 80

N_R = No. elements, receive = 40

θ_T = Transmit beamwidth = 54° x 2-2/3° (0.04 rad)

θ_R = Receive beamwidth = 20° x 2-2/3° (0.04 rad)

f = 12 kHz, λ(wavelength) = 0.125 m

τ = 7 ms, $c\tau/2$ = 5.5 m

P_o = Acoustic power = 4 kW

T = 1-15 s

Using the Harris system in conjunction with a multichannel tape recorder and land-based data processing facilities, synthetic aperture demonstration systems with the following sets of parameter could be built.

	Slow Speed	Normal Speed
v = velocity (m/s)	1.25	2.5
L_{TR} = 2vT (m)	3.0	6.0*
T = Interpulse period (s)	1.25	1.25
R_S = cT/2 (m)	875	875
Number of range cells	128	128

* Formed by the concatenation of two of the Harris 3.0-m apertures.

	Slow Speed	Normal Speed
ρ = resolution (m)	2.25	2.25
$L_T = \leq 2\rho$ (m)	≤4.5	≤4.5
$\theta_s = \rho/R$ rad	0.0025	0.0025
$L_s = \frac{\lambda}{2\theta} = \frac{0.125}{0.005}$ (m)	25	25
$T_D = L_s/v$ (s)	20	10
N = Number pulses used to synthesize synthetic aperture	16	8
Resolution of conventional system, $\rho = R\lambda/L_R$ (m)	38-42*	19-21*
Resolution improvement factor	16	8
Near field of receiver $\left(L_T^2/\lambda\right)$ (m)	72	288
Attenuation (absorption) dB	2.6	2.6
Coverage rate per side (km^2/h)	4	8

The slow-speed system requires only a single receive aperture and hence is less costly. However, the platform speed is limited by the real receive array length to 1.25 m/s (2.5 knots). Consequently, the coverage rate of 4 km^2/h per side is low.

The Harris system would have to be installed pointing horizontally rather than vertically downward. This may be a significant expense. The yaw errors could be removed by a Mk 19 gyrocompass, which can have a 1 to 2 mrad accuracy in this application.

A demonstration system of this type could be completed in one year, at a cost of about \$600k to \$800k including assembly, testing, and data processing and display.

* Formed by the concatenation of two of the Harris 3.0-m apertures.

REFERENCES

1. G. M. Walsh, Final Report, Feasibility Study, Synthetic Aperture Array Techniques for High Resolution Ocean Bottom Mapping, Report No. R593, 29 December 1967, and Phase 1A, Report No. R664, 31 July 1968, Raytheon Company, Portsmouth, Rhode Island.

2. J. E. Sanders, K. O. Emery, and E. Uchupi, "Microtopography of Five Small Areas of the Continental Shelf by Side Scanning Sonar," Geological Society of America Bulletin, Vol. 80, April 1969, pp. 561-572.

3. Ocean Bottom Scanning Sonar, Westinghouse Brochure, 1965.

4. P. J. Luke, "Far Field Pattern of Synthetic Aperture System," APL/JHU MRT-7-126, 1 May 1970.

5. A Proposal to Plan an Experiment Determining Ocean Acoustic Stability Relating to Synthetic Aperture Sonar, Raytheon Proposal #P 5548-0-51, 14 August 1970.

6. A. M. Chwastyk, "Synthetic Aperture Sonar Processing System," APL/JHU MPT-2-037, 6 July 1970.

7. R. J. Urick, Principles of Underwater Sound for Engineers, MacGraw-Hill, N.Y. (particularly section on Sea Bottom Reverberation, pp. 217-225).

8. B. C. Heezen, "Physiographic Provinces and Acoustic Domains," U.S. Navy Journal of Underwater Acoustics, Vol. 17, No. 1, January 1967.

9. MBAssociates Proposals and Report:

   a. Program Plan, Seabed Treaty Verification Study, MB-P-70/23, April 1970.

   b. Program Plan, Submarine Acoustic Cross-Section Study, MB-P-70/11.

   c. An Integral Equation Approach to Acoustic Scattering from Fluid-Immersed Elastic Bodies (Report), MB-TM-69/104.

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10. M. C. Junger, The Detection of Deep Submergence Hulls by Passive and Active Sonar, Cambridge Acoustical Associates, February 1962 (DDC 328210).

11. Narrow Beam Echo Sounder, Harris ASW Division Brochure, General Instrument Corp., Westwood, Massachusetts.